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Research Article

Speech Intensity Response to Altered Intensity Feedback in Individuals With Parkinson's Disease

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Purpose: Hypophonia (low speech intensity) is the most common speech symptom experienced by individuals with Parkinson's disease (IWPD). Previous research suggests that, in IWPD, there may be abnormal integration of sensory information for motor production of speech intensity. In the current study, intensity of auditory feedback was systematically manipulated (altered in both positive and negative directions) during sensorimotor conditions that are known to modulate speech intensity in everyday contexts in order to better understand the role of auditory feedback for speech intensity regulation.

Method: Twenty-six IWPD and 24 neurologically healthy controls were asked to complete the following tasks: converse with the experimenter, start vowel production, and read sentences at a comfortable loudness, while hearing their own speech intensity randomly altered. Altered intensity feedback conditions included 5-, 10-, and 15-dB reductions and increases in the feedback intensity. Speech tasks were completed in no noise and in background noise.

Results: IWPD displayed a reduced response to the altered intensity feedback compared to control participants. This reduced response was most apparent when participants were speaking in background noise. Specific task-based differences in responses were observed such that the reduced response by IWPD was most pronounced during the conversation task.

Conclusions: The current study suggests that IWPD have abnormal processing of auditory information for speech intensity regulation, and this disruption particularly impacts their ability to regulate speech intensity in the context of speech tasks with clear communicative goals (i.e., conversational speech) and speaking in background noise.

Parkinson's disease (PD) is a neurodegenerative movement disorder characterized by major motor features of rest tremor (3–5 Hz frequency), rigidity (increased, sustained muscle tone), akinesia (reduced number of spontaneous movements), bradykinesia (slowed movements), hypokinesia (reduced range of movements), postural instability, and speech symptoms classified as hypokinetic dysarthria. Hypophonia or low speech intensity has been found to be the most common speech symptom experienced by individuals with PD (IWPD), across age and disease duration (Adams & Dykstra, 2009; Darley et al., 1969; Duffy, 2013; Logemann et al., 1978; Wertheimer et al., 2014). Several studies have provided evidence of the impact speech intensity has on speech intelligibility (Adams et al., 2008; Andreeta et al., 2016; Dykstra et al., 2012). Reduced loudness has been implicated in reduced overall quality of life, withdrawal from social interactions, and decreased participation (Miller et al., 2006).

The specific pathological mechanism causing speech impairment in PD is unclear; however, it is hypothesized that sensory or sensorimotor integration deficits constitute this aspect of PD. Several theoretical models have been proposed to describe the basis of speech motor control. These models suggest an internal forward mechanism and that auditory feedback is critical for detection and correction of mismatches between intended and actual vocal output (Bays et al., 2005; Burnett et al., 1998; Houde & Nagarajan, 2011; Tourville et al., 2008; Voss et al., 2007; Wiener, 1948, as cited in Fairbanks, 1954; Wolpert &

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Ghahramani, 2000). It is predicted that evidence for a sensorimotor integration deficit hypothesis for speech production would be most apparent during an ongoing speech movement. If during a speech movement one experiences unexpected alterations of the sensory feedback (e.g., auditory, visual, proprioceptive), the system should be able to recognize the incongruence from the motor plan and adjust or compensate accordingly. For example, previous literature has described this type of compensatory response by neurologically healthy speakers (pitch, formant structure, and intensity perturbations) as a modification to speech production in the opposite direction to the alteration (Bauer et al., 2006; Burnett et al., 1998; Heinks-Maldonado & Houde, 2005; Purcell & Munhall, 2006; Tourville et al., 2008). Perturbation studies involve examination of the rapid and unexpected response to a brief (~200–500 ms) auditory perturbation to the speech signal (e.g., pitch, formant frequency, duration, intensity). In IWPD, studies of auditory perturbation (pitch and formant frequency) have found that patients exhibit an abnormal response to sensorimotor integration compared to control groups (larger magnitude of compensation, longer response peak and end durations; Chen et al., 2013; Huang et al., 2016; Kiran & Larson, 2001). Similarly, Liu et al. (2012) found larger response magnitudes to intensity perturbations by participants with PD compared to healthy controls.

An additional characteristic of speech motor control is the capacity to adapt to novel conditions. Adaptation to continuous and predictable auditory perturbations have demonstrated that healthy speakers are capable of adapting their speech motor strategies (see Perkell, 2012, for a review). Studies on the adaptation response to perturbed auditory feedback (fundamental frequency and first formant shifts) in PD found reduced responses by IWPD in comparison to control participants (Abur et al., 2018; Mollaei et al., 2013). These results have been interpreted to suggest that, in PD, although an error signal is detected and corrected by the feedback control system, there is an impaired ability to update the feedforward control system, resulting in a reduced adaptation response (Abur et al., 2018).

In IWPD, it has been suggested that hypophonia may be a result of auditory–motor integration deficits (Adams & Dykstra, 2009). The error correction ability during altered intensity feedback (AIF) in IWPD may be abnormal, and further examination of this abnormality may provide insight into which part of the process is disrupted.

AIF

Unlike the brief and rapid (~200–500 ms) alterations in feedback used in perturbation and adaptation paradigms, the AIF paradigm involves the continuous alteration of feedback across complete utterances or across multiple utterances (i.e., conversation or reading passage). The AIF paradigm has been previously referred to as the side tone paradigm in the field of telephony because of the original focus on early telephone operators hearing their own speech intensity altered by the simultaneous (side tone) headphone feedback. In the current context, which is less concerned with telephony and focused on concerns about auditory intensity feedback regulation in speech disorders such as PD, the authors prefer to use the term *altered intensity feedback*.

The AIF manipulation causes the participant to hear their speech at an altered (increased or decreased) intensity than is actually produced. This results in a healthy speaker adjusting their intensity to speak at a quieter loudness when hearing increased intensity feedback as a presumed compensatory response (Ho et al., 1999; Lane et al., 1961, 1969; Siegel & Pick, 1974). Few previous studies have examined responses to AIF in PD. Ho et al. (1999) found that IWPD failed to adjust their intensity in a conversation task, implying disrupted loudness perception. This study did not evaluate the response of participants with PD to decreased intensity feedback; however, the magnitude of the response to reduced intensity feedback may not be similar to the response to increased intensity feedback. In addition, should a response to decreased intensity feedback result in increased speech intensity, there may be an opportunity for AIF to be used for therapeutic or speech management purposes.

Although similar to the adaptation paradigm used by Abur et al. (2018), as the AIF procedure involves a presumed adaptation to the altered feedback, the current paradigm extends to include continuous alteration of feedback over longer durations and across more complex speech tasks. Intensity regulation involves the complex processing of external cues or conditions; in typical conversational settings, the speaker must monitor the environment and their own speech intensity levels in order to compensate for such factors as ambient or background noise in their surroundings and how near or far their listener is situated. The varied contexts that a speaker experiences necessarily mean that processing of additional factors such as distance, communicative intent, and cognitive load is all implicated in the regulation of speech intensity in naturalistic contexts.

Interestingly, although Ho et al. (1999) found a possible disrupted loudness perception in a conversation task, this and another study of continuous AIF report that, during reading and counting tasks, the PD group responded similarly to controls (Coutinho et al., 2009; Ho et al., 1999). This is suggestive of a possible task effect. Due to limited previous research, the impact of AIF on PD-related speech intensity regulation in a range of speaking conditions and speech tasks requires further exploration.

Background Noise

The Lombard effect (Lombard, 1911) is the phenomenon in which a person increases their speech intensity when speaking in a noisy environment. This observation remains consistent across reading and conversational tasks, with several studies providing evidence of healthy speakers increasing their intensity with increasing levels of background noise and decreasing their speech intensity once the noise is stopped (Adams, Dykstra, et al., 2006; Ho et al., 1999; Lane & Tranel, 1971; Pick et al., 1989). Previous work suggests an "overall gain reduction" for speech intensity in IWPD when speaking in noise (Adams, Dykstra, et al., 2006; Ho et al., 1999). This is because IWPD spoke at a consistently lower intensity despite producing sequentially increased intensity responses across increasing background noise levels (Adams, Dykstra, et al., 2006; Ho et al., 1999).

Speech Tasks

Speech intensity can be obtained across a vowel, a sentence, and a breath group or utterance within speech (Adams et al., 2005; Huber & Darling, 2012; Neel, 2009). The nature of the speech task has an influence on the regulation of speech intensity (Fox & Ramig, 1997; Rosen et al., 2005). Quasispeech tasks include those that do not necessarily represent natural speaking intensity (e.g., vowel production compared to conversational tasks; Rosen et al., 2005). Junqua et al. (1999) found speech intensity increased more in background noise (Lombard effect) during conversational speech than in a reading task. The effect of speech task on speech intensity regulation is also exemplified by work conducted by S. Patel et al. (2014). These researchers found healthy participants regulate speech intensity (during perturbed feedback) only in speaking contexts that require a specific linguistic goal, specifically relating to emphatic stress in a sentence. However, it is possible that suprasegmental and segmental aspects of speech may be controlled by different mechanisms for which auditory feedback plays different roles (Perkell et al., 2007).

Interestingly, whereas neurologically healthy control participants show a tendency to increase their intensity when speaking in conversational tasks, particularly those with added cognitive requirements (i.e., speaking about personal experiences), participants with PD do not make a similar adjustment (Ho et al., 1999; Winkworth et al., 1994). A study by Moon (2005) found a greater reduction in speech intensity during conversational tasks compared to reading.

Despite the work that has been conducted on speech intensity perception and production in IWPD, there is a paucity of literature that has examined sensorimotor integration for speech production in the speech intensity domain. This study aimed to (a) examine IWPD's speech intensity response to AIF and determine whether this response varied depending on the direction of the AIF (positive vs. negative direction). In addition, examination of sensorimotor integration in the context of the range of communicative situations (such as speaking in background noise or speaking with different interlocuter distances) and a range of speech tasks experienced by these individuals is needed. Thus, this study also aimed to (b) examine the role that auditory sensory feedback plays in PD-related intensity control during speech tasks, including socially driven speech tasks, and (c) in the naturalistic context of speaking in background noise, which is known to impact speech intensity. It is hypothesized that IWPD will display a reduced response to the altered feedback in both altered intensity directions (positive and negative), across all speech tasks, and have particular difficulty modulating their speech in the context of background noise.

Method

Participants

Twenty-six IWPD (19 men and seven women, 69.38 ± 6.38 years old) and 24 neurologically healthy control participants (eight men and 16 women, 73.29 ± 5.98 years) were included in the study (following the exclusion of one participant with PD due to his inability to complete the full study protocol for scheduling reasons, exclusion of one control participant due to a technical issue with the audio recording, and another control participant not meeting eligibility criteria for no prior speech disorder). There was no significant difference in age between the PD and control groups, $t(48) = -1.517$, $p = .136$. Participants with PD were recruited from patients seen by a movement disorder neurologist and were diagnosed by him as having idiopathic PD and some degree of hypophonia. To classify hypophonia severity, a simple clinical judgment of mild, moderate, or severe hypophonia was carried out by the first author with 10+ years' experience of working with IWPD. These ratings were made during the initial study visit while the patient produced conversational speech in a quiet room at a listener-to-talker distance of 2 m. Control participants were recruited from the Research Retirement Association in London and the Western University Alumni Association. Exclusion criteria for all participants included having no other speech-language impairments besides those resulting from a diagnosis of PD, cognition (assessed using the Montréal Cognitive Assessment) in the normal range (> 22; Nasreddine et al., 2005), and passing a binaural hearing screen with thresholds of 40 dB HL at 0.25, 0.5, 1, and 2 kHz frequencies. Participants with PD were stabilized on their antiparkinsonian medication and were tested approximately 1 hr after taking their regularly scheduled dose. The mean disease duration since diagnosis was 8.08 ± 5.09 years, and mean Unified Parkinson's Disease Rating Scale Part III (Goetz et al., 2007) score was 24.02 ± 7.60. All participants provided written consent for participation in the study, and the research protocol was approved by the Human Subjects Research Ethics Board (Western University Ethics No. 109016). Demographic information for participants with PD is reported in Table 1.

Apparatus

All participants were seated in an audiometric booth for the duration of the study. Participants were provided with a standard set of audiometric headphones (Telephonics 51OCO17-1) and headset microphone (AKG C520) attached to a preamplifier (M-Audio preamp USB), an audiometer (GSI-10, model 1710), and a desktop computer. A schematic of the experimental setup is provided in Figure 1. The microphone was placed 6 cm from the midline of the participant's mouth. Calibration of the microphone was established through the use of a sound level meter placed 15 cm (6 in.) from the participant's mouth while they produced three short (< 5 s) "ah" sounds at 70 dBA SPL. The recording module in Praat software (Boersma & Weenink, 2011) was used to digitize the speech samples at 44.1 kHz

Table 1. Participants with Parkinson's disease (PD) demographic information.

Participant	Gender	Age	PD duration	Hypophonia severity
PD 01	F	68	7	Mild
PD 02	M	71	13	Moderate
PD 03	M	78	NA	Moderate
PD 04	M	69	6	Moderate
PD 05	M	80	14	Moderate
PD 06	M	69	12	Mild
PD 07	M	75	4	Moderate
PD 08	F	56	3	Moderate
PD 09	M	66	10	Mild
PD 10	M	83	9	Moderate
PD 11	M	68	3.5	Mild
PD 12	M	70	13	Mild
PD 13	M	71	5	Moderate-severe
PD 14	M	74	2	Mild-moderate
PD 15	M	69	10	Mild
PD 17	M	74	2.5	Mild
PD 18	M	63	6	Mild
PD 19	M	78	3	Mild
PD 20	M	73	7	Mild
PD 21	M	63	7	Moderate
PD 22	F	73	25	Mild
PD 23	F	74	11	Mild
PD 24	M	72	8	Moderate
PD 25	F	54	5	Mild
PD 26	F	68	4	Moderate
PD 27	F	64	12	Mild

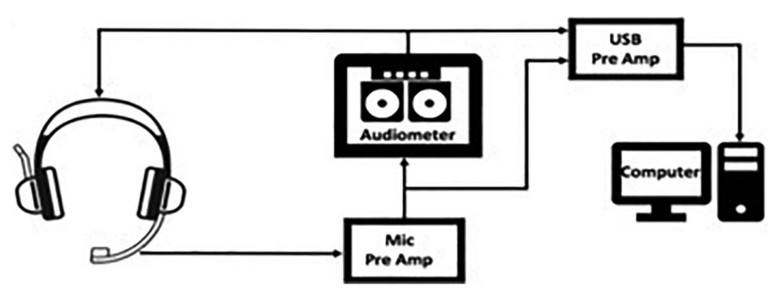
Note. Hypophonia severity = as rated by experimenter; F = female; M = male; NA = data not available.

and 16 bits. During speech tasks, the audiometer was used to alter the intensity of the participant's speech. The headphone output was calibrated to the input microphone using speech noise produced by the audiometer and an audio speaker placed 6 cm from the headset microphone. The calibration of the output of the headphones was accomplished with an earphone coupler (Bruel & Kjaer, Type 4152) attached to a sound level meter (Bruel & Kjaer, Type 2203).

Procedure

This study was part of a larger experimental procedure that included additional speech tasks and conditions. The order of speech tasks analyzed for the current study were as follows: (1) conversation with the experimenter (1 m, near interlocutor distance), (2) conversation with the experimenter (6 m, far interlocutor distance), (3) vowel production (4–5 s of sustained "ah"), and (4) reading at habitual speech intensity (standard sentence that includes a variety of consonant and vowel sounds; useful in the acoustic analysis of PD speech "She saw patty buy two poppies"; Abeyesekera et al., 2019; Knowles et al., 2018). Throughout each of the tasks listed above (Tasks 1–4), the participants received randomly presented AIF related to their own speech. The random AIF conditions included two repetitions of the following seven AIF conditions: 5-, 10-, and 15-dB reductions in the feedback intensity; 5-, 10-, and 15-dB increases; and 0 dB or no alteration in the feedback intensity. These tasks were first completed in no noise and then repeated in 65 dB SPL of multitalker background noise (four-talker Audiotec recording). Participants were naïve to the altered feedback conditions. AIF was initiated following instructions for each task, just prior to participant speech production, and was terminated once the participant completed the requested task. For the conversation tasks, participants were requested to discuss familiar topics with the experimenter for about five to 10 utterances per altered feedback condition. Topics included family, hobbies, occupational experiences, interests, and recent vacations. Instances of noticeably high emotionally laden utterances during which the participant was visibly upset were excluded from analysis (e.g., discussions that naturally progressed to death of a loved one). In these rare instances, additional samples of speech for that AIF condition were elicited and were used to replace the emotionally laden utterances. Several acoustic differences (e.g., longer vowel durations, longer voice onset times) have been previously associated with vowel and reading tasks (Brown & Docherty, 1995; Kent et al., 1997), and so to avoid this potential influence on the conversation tasks, the conversation tasks were completed first. The full study protocol was typically completed in a single session, with an average duration of 2.75 hr (range: 2.5–3 hr), including components of the experiment that were not analyzed for the current study. Participant visits were scheduled so as to minimize possible fatigue; however, no direct measures of fatigue were obtained for the current study. Fatigue can be a debilitating symptom in PD (Friedman et al., 2011) and has been associated with reduced communication participation

Figure 1. Schematic representation of the experimental setup.



(McAuliffe et al., 2017) and increased effort while speaking (Solomon & Robin, 2005). Therefore, future AIF studies should include measures of perceived fatigue. However, a study by Makashay et al. (2015) indicated an overall fatigue-resistant speech system in PD speakers. For the measurement of speech intensity in all conditions and tasks, the recorded speech audio files were measured off-line using the acoustic intensity measurement module in the Praat program. Using Praat, long (+250 ms) unvoiced segments or pauses were selectively removed, and the root-mean-square intensity contour method was used to obtain the average intensity for each utterance.

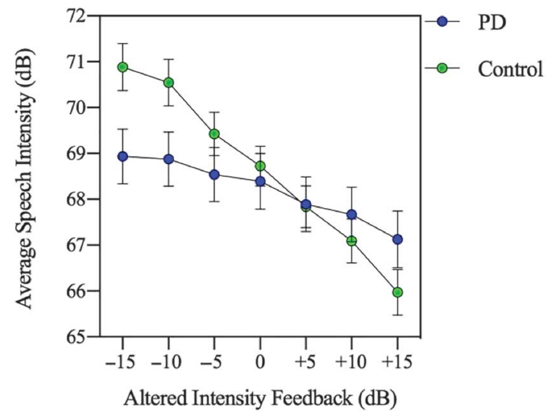
To examine the effect of AIF on speech intensity responses in PD and control groups, a two-way repeated-measures analysis of variance (ANOVA) with the between-subjects factor of group (control and PD) and within-subject factor of AIF condition (−15, 10, −5, 0, +5, +10, and +15 dB) was conducted (collapsed across all tasks and conditions).

To examine the impact of speaking task and noise condition, a linear regression analysis was first performed on each participant's data using the speech intensity response values and the corresponding values relating to each of the seven AIF conditions (−15 to +15 dB). R^2 values (coefficient of determination) from each participant's regression slopes were averaged, with mean values ranging from .33 to .78 across speaking tasks and conditions. Mean and standard deviation R^2 for each speech task are provided in Table 5. From each of these individual participant regression analyses, an individual slope value of the AIF response was obtained and was used to compare the group responses. A three-way ANOVA involving the between-subjects factor of group (control and PD), the within-subject factor of speech tasks (conversation near, conversation far, vowel, and sentence reading), and the within-subject factor of noise (background noise and no noise) was used to examine any possible task and noise condition effects on the AIF slope in the two groups. To examine possible zero-intercept differences (slope intercept), an additional three-way ANOVA with the between-subjects factor of group and the within-subject factors of speech tasks and background noise condition was conducted with the zero-intercept dependent measure. All analyses were followed by post hoc analyses and Bonferroni correction for multiple comparisons.

Results

The group speech intensity responses to AIF across all speech tasks and noise conditions are illustrated in Figure 2. For the two-way (Group × AIF Feedback condition) ANOVA, the sphericity assumption was not met (< .05), and Greenhouse–Geisser correction was used for all subsequent analyses. Results indicated that there was no significant main effect of group, $F(1, 46) = 0.327$, $p = .570$, with IWPD having a similar marginal mean ($M = 68.204$, $SD = 2.98$) to that of the control group ($M = 68.639$, $SD = 2.21$). In contrast, there was a significant main effect of AIF condition on speech intensity, $F(6, 276) = 197.48$, $p = .000$, $\eta_p^2 = .811$. A post hoc analysis was used to examine the pairwise comparisons related to the seven feedback conditions (see Table 2), which showed a general trend of increasing speech intensity response with decreasing AIF conditions. In addition, the Group × Feedback condition interaction was statistically significant, $F(6, 276) = 42.55$, $p = .000$, $\eta_p^2 = .481$, for speech intensity. Group descriptive statistics are provided in Table 3. To examine the interaction in more detail, nine of the potential 21 pairwise interaction post hoc analyses were selected, as these are of primary interest (see Table 4). These include the six post hoc analyses related to the zero versus other conditions and the three post hoc analyses related to the positive (+) versus negative (−) conditions at the three feedback levels (Levels 5, 10, and 15). For the zero versus other condition comparisons, five of the six post hoc analyses were significant. These post hoc results indicate that the absolute size of the compensation response, both in the negative and positive directions, was significantly and consistently lower for the participants with PD relative to the controls.

Figure 2. Marginal means for the Parkinson's disease (PD) and control groups and the seven altered intensity feedback (AIF) conditions.



With regard to the three interaction post hoc analyses involving the negative versus positive feedback conditions, the results indicate the absolute size of the response intensity in the negative feedback conditions was significantly and consistently smaller for the IWPD relative to the control participants. In addition, although not analyzed statistically, it was noted that IWPD displayed variable responses, including following responses to AIF (i.e., speech intensity response in the same direction as the altered feedback).

Slope Analysis

The group speech intensity results and Figure 2 indicated a difference in the AIF function for the PD and control groups. It also appeared that the function is a near-linear relationship that could be approximated by the slope of a linear regression. Results of the three-way (Group × Speech Task × Background Noise condition) ANOVA indicated that the assumption of sphericity was violated and

Table 2. Post hoc results related to pairwise comparisons involving the marginal means for the seven altered intensity feedback conditions: –15, –10, –5, 0, +5, +10, and +15 dB.

Feedback conditions	*M*	*SD*	Pairwise comparisons and *p* values						
			–15	–10	–5	0	+5	+10	+15
–15 dB	69.91	2.76							
–10 dB	69.71	2.73	.291						
–5 dB	68.98	2.65	< .001*	< .001*					
0 dB	68.56	2.64	< .001*	< .001*	< .001*				
+5 dB	67.87	2.63	< .001*	< .001*	< .001*	< .001*			
+10 dB	67.38	2.69	< .001*	< .001*	< .001*	< .001*	< .001*		
+15 dB	66.55	2.78	< .001*	< .001*	< .001*	< .001*	< .001*	< .001*	

*Significant at $p < .002$ (.05/21 comparisons).

Greenhouse–Geisser correction was used for all subsequent analyses. The results indicated a main effect of group, $F(1, 43) = 60.59$, $p = .000$, $\eta_p^2 = .585$, such that the PD group had a significantly lower (flatter) slope ($M = -.061$, $SD = .043$) compared to the steeper negative slope of the control group ($M = -.167$, $SD = .047$). Figure 3 depicts this group difference (group regression lines and slope function). Note that the negative slope values suggest that, as the AIF values increased, the speech intensity that was produced decreased. Results also revealed a significant main effect of speech task, $F(2.35, 101.04) = 17.434$, $p = .000$, such that the only significant differences were between the reading task (reduced slope) and all other tasks (reading $M = -.075$, conversation near $M = -.118$, conversation far $M = -.120$, vowel $M = -.142$). The slope values of the four speech tasks in the PD and control groups are presented in Table 5. A significant main effect of background noise was found, $F(1, 43) = 11.717$, $p = .001$, $\eta_p^2 = .214$, such that a significantly reduced slope was produced by both groups in the no-noise condition ($M = -.099$, $SD = .047$) compared to the steeper slope produced in the 65-dB noise condition ($M = -.129$, $SD = .060$).

The Group × Speech Task interaction was statistically significant, $F(2.35, 101.04) = 26.96$, $p = .000$, $\eta_p^2 = .385$, and a pairwise analysis of simple main effects showed that, in the PD group, the vowel task led to a statistically significant increased slope ($M = -.099$, $SD = .047$) compared to all other tasks, and in the control group, the reading task led to a reduced slope ($M = -.099$, $SD = .047$) compared to all other tasks. A post hoc interaction analysis is provided in Table 6. Figure 4 shows the slope values for each group across the four speech tasks. A post hoc analysis and a visual analysis of the graph can be used to highlight the Group × Speech Task interaction results. For example, the control participants show a much larger negative slope than the participants with PD for the conversation tasks, but these group differences in the slope values are less pronounced and almost converge during the vowel and reading tasks. Thus, the group differences in slope values are most pronounced in the conversation tasks compared to the reading and vowel tasks.

Table 3. Marginal means and standard deviations related to the seven altered intensity feedback (AIF) conditions obtained for the Parkinson's disease (PD; $n = 25$) and healthy control (HC; $n = 23$) groups.

AIF conditions	PD		HC	
	M	*SD*	*M*	*SD*
–15 dB	68.93	2.99	70.88	2.48
–10 dB	68.88	2.97	70.54	2.45
–5 dB	68.54	2.96	69.43	2.25
0 dB	68.39	3.06	68.72	2.09
+5 dB	67.89	2.98	67.84	2.18
+10 dB	67.67	3.00	67.09	2.29
+15 dB	67.13	3.10	65.97	2.37

Results of the ANOVA revealed an interaction of Background Noise × Group, $F(1, 43) = 5.354$, $p = .026$, $\eta_p^2 = .111$. Figure 5 presents these findings, and these are also reflected in the post hoc analysis of the interaction, which revealed a significantly reduced slope was produced by both groups in the no-noise condition ($M = -.10$, $SD = .05$) compared to the steeper slope produced in the 65-dB noise condition ($M = -.13$, $SD = .06$). A within-group analysis revealed that the PD group had slope values that were similar across the noise conditions (no noise $M = -.056$, $SD = .038$; 65-dB noise $M = -.066$, $SD = .043$; $p = .29$), while the control group showed a significant difference in slope values across the noise conditions (no noise $M = -.141$, $SD = .52$; 65-dB noise $M = -.192$, $SD = .080$; $p = .003$). An interaction post hoc analysis of difference scores revealed the noise condition difference (PD: no noise vs. 65-dB noise $M = -.01$, $SD = .05$; control: no noise vs. 65-dB noise $M = -.05$, $SD = .07$) was significantly different ($p < .05/2$ comparisons = .025) across the two participant groups (difference score $M = .04$, $SE = .02$, $p = .019$). This slope analysis indicates that the control participants produced a steeper AIF function compared to the participants with PD and that this group difference in the AIF slope becomes greater in the context of background noise.

The Task × Background Noise interaction was also statistically significant, $F(2.53, 108.65) = 3.204$, $p = .033$, $\eta_p^2 = .069$. A post hoc analysis revealed a difference between the reading task (increased slope) compared to all other tasks in no noise ($p < .005$), whereas in 65-dB noise,

Table 4. Post hoc comparisons related to the feedback condition versus group interaction.

Difference conditions	PD *M*	PD *SD*	HC *M*	HC *SD*	PD–HC difference score: Mean difference	PD–HC difference score: Standard error difference	*t*	*p*
−15 vs. 0	−0.49	0.73	−2.12	1.02	1.64	0.25	$t(48) = 6.46$	< .001*
−10 vs. 0	−0.44	0.59	−1.79	0.94	1.35	0.22	$t(48) = 6.05$	< .001*
−5 vs. 0	−0.13	0.66	−.70	0.58	0.57	0.18	$t(48) = 3.26$	.002*
+5 vs. 0	0.52	0.64	0.86	0.61	−0.34	0.18	$t(48) = -1.92$	.060
+10 vs. 0	0.73	0.58	1.57	0.72	−0.84	0.18	$t(48) = -4.59$	< .001*
+15 vs. 0	1.30	0.79	2.68	1.06	−1.38	0.26	$t(48) = -5.31$	< .001*
−15 vs. +15	−1.78	1.05	−4.80	1.71	3.01	0.26	$t(48) = 7.48$	< .001*
−10 vs. +10	−1.17	0.75	−3.36	1.33	2.19	0.21	$t(48) = 7.16$	< .001*
−5 vs. +5	−0.65	0.61	−1.56	0.77	0.92	0.16	$t(48) = 4.69$	< .001*

Note. These post hoc analyses include a series of *t* tests involving the feedback condition difference scores versus group difference scores. The post hoc analyses focused on the zero versus other feedback conditions and the corresponding positive versus negative feedback conditions (i.e., +15 vs. −15 dB) instead of examining all possible pairwise comparisons. PD = Parkinson's disease; HC = healthy control.
*Significant at $p < .005$ (.05/9 comparisons).

the reading task was only significantly different from the vowel prolongation ($p < .005$).

Finally, there was a significant three-way interaction involving group, speech task, and background noise, $F(2.53, 108.65) = 6.515$, $p = .001$, $\eta_p^2 = .132$. To better understand this three-way interaction, two separate graphs were created for each of the noise conditions (see Figures 6 and Figure 6a and 6b). Examination of these graphs reveals that, during the no-noise condition, the IWPD and controls show different patterns that reflect the previously described two-way Group × Task interaction. Thus, the Group × Task interaction, with a greater group difference in the conversation tasks, is further exaggerated in the context of background noise. For example, the IWPD had a slope value for the conversation near task that was similar to the reading task while the controls had a steeper slope for the conversation near task relative to the reading task. This Group × Task interaction becomes even greater when the 65-dB noise is introduced. Table 7 provides a post hoc analysis of the three-way interaction. The two significant three-way post hoc analyses (and one approaching statistical significance) involve the conversation at a near distance task.

The zero-intercept was also analyzed using a three-way (Group × Speech Task × Background Noise condition) ANOVA. There was a significant main effect of task, $F(2.32, 106.50) = 69.41$, $p = .000$, $\eta_p^2 = .601$ (post hoc with Bonferroni correction revealed conversation at a far distance and the vowel task were both greater than conversation at a near distance, which was greater than the intercept during the reading task) and a main effect of background noise, $F(1, 46) = 24.77$, $p = .000$, $\eta_p^2 = .350$ (65-dB noise intercept was greater than in no noise). The Task × Background Noise interaction was also statistically significant, $F(2.53, 108.65) = 3.204$, $p = .033$, $\eta_p^2 = .069$. A post hoc analysis revealed an increased intercept in conversation far and vowel compared to conversation near and reading in no noise ($p < .005$), whereas in 65-dB noise, all tasks differed from each other ($p < .005$) with the exception of the vowel task and conversation at a near distance. Neither the main effect

Figure 3. Group regression lines and slope value across all speech tasks and noise conditions in the Parkinson's disease (PD; solid blue line) and control (dashed red line) groups. Shaded variance bands represent 95% confidence interval.

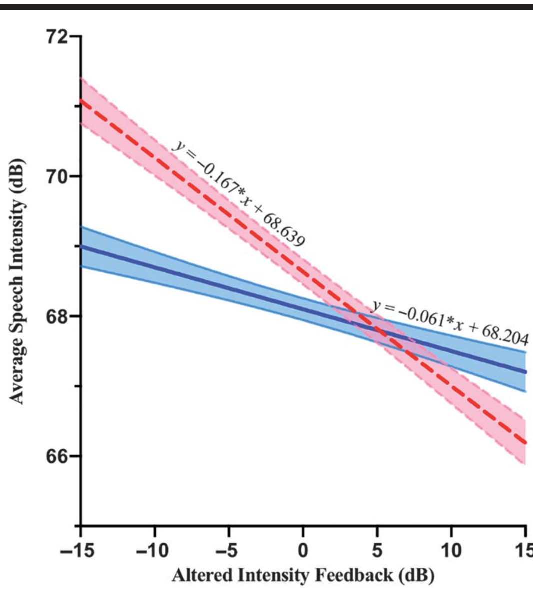


Table 5. Descriptive statistics for the slope values of the four speech tasks in the Parkinson's disease (PD) and control groups.

Speech task	PD *M*	PD *SD*	R^2 *M*	R^2 *SD*	Control *M*	Control *SD*	R^2 *M*	R^2 *SD*
Conversation (near)	−.032	.05	.333	.19	−.205	.08	.460	.14
Conversation (far)	−.042	.06	.385	.20	−.198	.06	.782	.15
Vowel	−.116	.07	.616	.22	−.167	.07	.760	.18
Reading	−.054	.03	.400	.24	−.097	.06	.548	.27

Note. R^2 values denote coefficient of determination.

Table 6. Post hoc analyses related to the two-way interaction involving group and speech tasks.

Difference conditions	PD		Control		PD–control difference score *t* test			
	Mean difference	*SD*	Mean difference	*SD*	Mean difference	Standard error difference	*t*	*p*
ConvoNear–ConvoFar	−0.021	0.064	0.005	0.067	−0.025	0.018	*t*(48) = −1.37	.175
ConvoNear–Vowel	−0.084	0.074	0.037	0.066	−0.121	0.020	*t*(48) = −6.05	< .001*
ConvoNear–Reading	−0.025	0.046	0.110	0.051	−0.134	0.014	*t*(48) = −9.74	< .001*
ConvoFar–Vowel	−0.064	0.090	0.032	0.072	−0.095	0.023	*t*(48) = −4.09	< .001*
ConvoFar–Reading	−0.004	0.059	0.105	0.067	−0.109	0.018	*t*(48) = −6.07	< .001*
Reading–Vowel	0.059	0.056	0.073	0.047	−0.014	0.015	*t*(48) = −0.93	.358

Note. The mean difference scores between conditions are shown for each group on the left side of the table. The mean group difference score and the related *t* value and *p* value for the post hoc interaction comparison are shown on the right hand side of the table. The four speech tasks are labeled as follows: ConvoNear–ConvoFar, ConvoNear–Reading, ConvoNear–Vowel, ConvoFar–Reading, ConvoFar–Vowel, and Reading–Vowel. PD = Parkinson's disease; ConvoNear = conversation (near); ConvoFar = conversation (far).

*Significant at $p < .008$ (.05/6 comparisons).

of group nor any other interactions were statistically significant at $p < .05$ (see Appendix for ANOVA results and descriptive statistics).

Discussion

Sensorimotor integration deficits have been hypothesized as an explanation for several of the clinical symptoms associated with PD, including hypokinesia and bradykinesia (Bronstein et al., 1990; Klockgether & Dichgans, 1994; Rinalduzzi et al., 2015; Schneider et al., 1986; Tatton et al., 1984). Hypophonia in IWPD may be related to abnormal auditory perception or auditory–motor integration processes (Brajot et al., 2016; Coutinho et al., 2009; Ho et al., 1999).

In the current study, most participants (PD and control) displayed a compensatory response to the AIF levels, such that, as AIF levels increased, the speech intensity of participants decreased and vice versa. However, the response to AIF was different between the two groups. Specifically, IWPD were observed to produce a reduced magnitude of the response in all AIF conditions, and the slope of the AIF function was significantly reduced in the PD group. This difference was observed despite the lack of a significant difference between the two groups' speech intensity (lack of group effect in a zero-intercept analysis), suggesting this pattern is observable even in mild hypophonia. Compared to previous studies, the current protocol included AIF in the negative direction, and Table 4 suggests that IWPD were observed to produce a reduced magnitude of the response in both positive- and negative-direction AIF conditions. Interestingly, when the negative and positive directions were compared, the magnitude of the compensation response was significantly less in the negative direction in the PD group. This directional difference (less in the negative direction)

Figure 4. Average slope values for all tasks in the Parkinson's disease (PD) and control groups. AIF = altered intensity feedback.

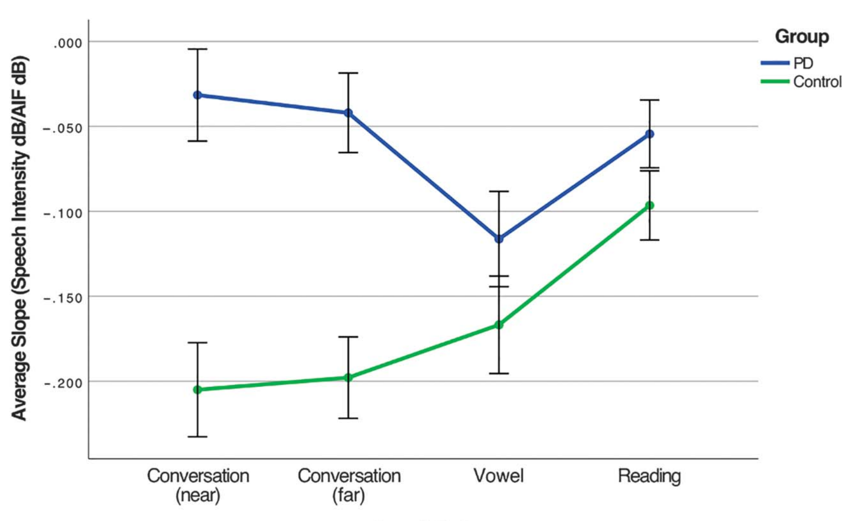
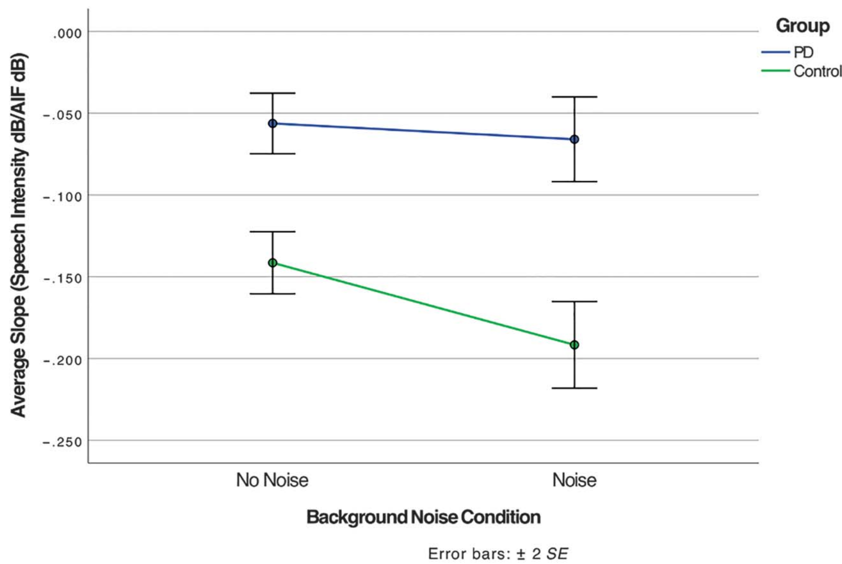


Figure 5. Average slope values for background noise and no background noise in the Parkinson's disease (PD) and control groups. AIF = altered intensity feedback.



could be related to the observation that loudness decreases may be perceived as smaller than similar amounts of increase in intensity (Larson et al., 2007). It is also possible that a reduced relative importance of decreased loudness to the auditory–motor system exists such that mechanisms to control for increased loudness are more "primed" for regulation, as only louder speech has the potential to be damaging and uncomfortable to the speaker. Still, why this may be occurring to a greater degree in the IWPD is unclear and requires further investigation. Overall, the data fit with the assumptions of the theoretical models of speech motor control, as the reduced magnitude of the response in IWPD suggests that the detection and correction processes of mismatches between intended and actual vocal output may be disrupted. In addition, individual responses were qualitatively different between groups. Whereas all control participants showed compensation to altered feedback, IWPD displayed highly variable responses, including following responses to AIF (i.e., same direction as the altered feedback).

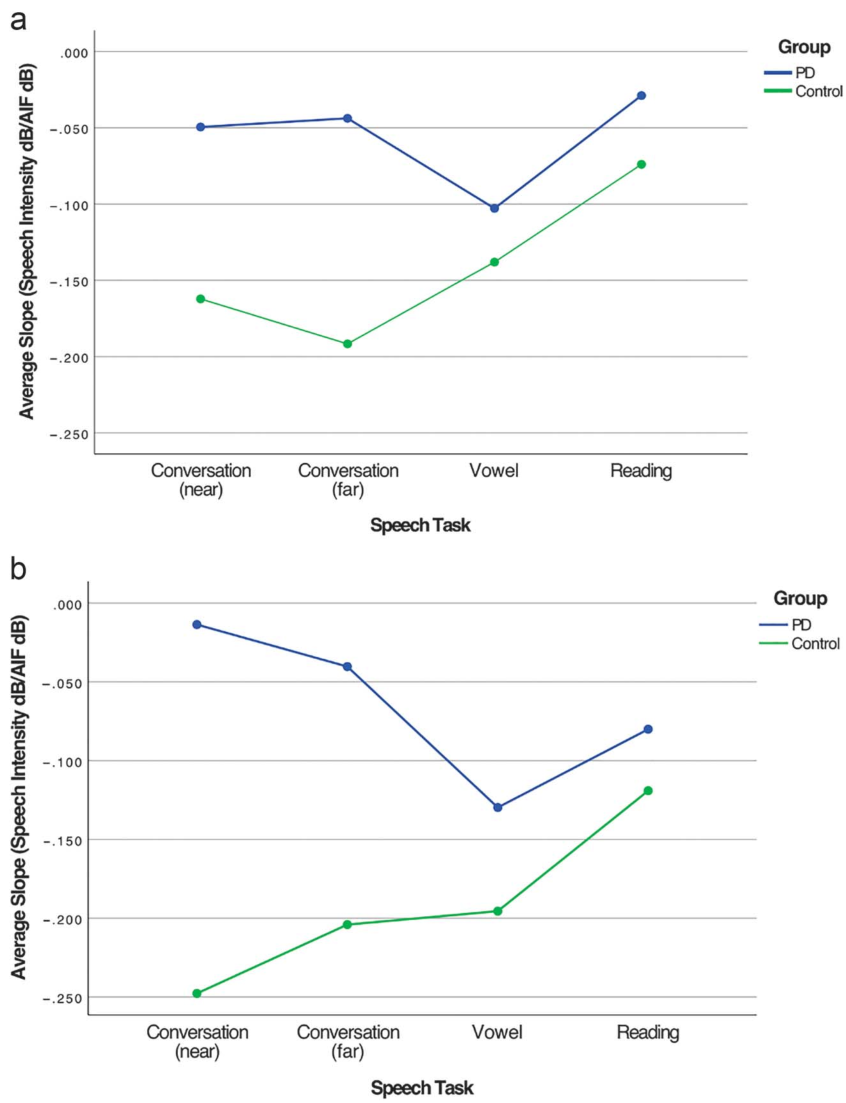
The AIF paradigm in the current study involves continuous alteration in feedback over the duration of multiple utterances involving many types of speech tasks, including conversational speech. It is similar to what could be termed the *continuous altered auditory feedback* paradigms that are used in studies of delayed auditory feedback or studies of the Lombard response. These continuous altered auditory feedback procedures all involve a presumed adaptation to the altered feedback, but the paradigms are not referred to as adaptation studies. Previous auditory–speech adaptation studies have found reduced adaptation to first formant alterations in IWPD (Mollaei et al., 2013, 2016). The AIF paradigm contrasts with perturbations, which occur at a discrete point in a word or vowel production of these studies; however, a study by Abur et al. (2018) extended the altered fundamental frequency auditory alteration for the duration of the participant's vowel production and found reduced adaptation responses in IWPD. It is therefore possible that the current AIF study and the adaptation paradigm used by Abur et al. are converging on similar sensorimotor results and that the current AIF study involves sensorimotor adaptation to intensity alterations. It is possible that the reduced response to AIF in the current study is related to similar impaired feedforward processes suggested by Abur et al.

The speech sensorimotor adaptation differs from the AIF paradigm in that adaptation studies include numerous trials and focus on quasispeech tasks (e.g., vowel production). In addition, "ramp" procedures with sequentially increasing or decreasing altered feedback across numerous trials either pre or post "hold" phase are included. Importantly, speech adaptation procedures (whether auditory or somatosensory) involve examination of learning *aftereffects,* such that the altered feedforward motor commands resulting from the altered feedback conditions are apparent following the removal of altered feedback (Barbier et al., 2020; Baum & McFarland, 1997; Houde & Jordan, 1998; Shiller et al., 2009; Villacorta et al., 2007). The current study did not examine potential aftereffects of AIF, and instead, the analyzed speech samples were selected from the midsections of vowel and utterance productions. This is a potential limitation of the current study and presents an opportunity for future research to examine the dynamic adaptation processes that may be occurring in the AIF paradigm.

Speech Tasks

Previous research suggests that IWPD produce increased speech intensity during speech tasks that do not have clear communicative goals, such as vowel phonation, syllable

Figure 6. (a) Average slope values for all tasks completed in no background noise in the Parkinson's disease (PD) and control groups. (b) Average slope values for all tasks completed in 65-dB background noise in the PD and control groups. AIF = altered intensity feedback.



repetition, and sentence reading compared to monologue tasks (Fox & Ramig, 1997; Ramig & Dromey, 1996; Ramig et al., 1996). In addition, unlike control participants who increase their speech intensity when speaking in conversation, IWPD display a greater reduction in speech intensity during conversational tasks (Ho et al., 1999; Winkworth et al., 1994). In the context of the AIF paradigm, the PD group produced reduced compensations to the altered feedback, specifically in the context of having a conversation. Adams and Dykstra (2009) hypothesized that the compounded attentional demands associated with a conversation task may have an impact on speech intensity regulation. Based on this hypothesis, if increased attentional demands are forcing the PD group to produce reduced compensations in the conversation task, then increased responses to the AIF (in comparison to the conversation task) are expected in the reading task (presumably less demanding of attentional resources). It is important to note, however, that responses to the AIF by the PD group in conversation (far distance) and the reading task were similar in the current study (see Table 5). Thus, alternative explanations for the more apparent reduced response by the PD group in the conversation tasks are warranted.

A communicative goal hypothesis is suggested as a novel description of this phenomenon. The increased communicative goals or demands associated with the conversation task provide a possible explanation. Perhaps speakers engage in different feedback processes or place increased priority on auditory feedback of their own voice when engaged in speech tasks requiring clear communicative goals

Table 7. Slope post hoc tests related to the three-way interaction involving Group × Task by noise condition.

Task difference	No Noise		65-dB noise		No–65 dB noise (PD) vs. no–65-dB noise (HC) difference	3-way post hoc	
	PD	HC	PD	HC			
	Mean difference (*SD*)	Mean difference (*SD*)	Mean difference (*SD*)	Mean difference (*SD*)	Mean difference (*SD*)	*t*	*p*
ConN–ConF	–.01 (.05)	.03 (.07)	.03 (.08)	–.04 (.08)	–.11 (.03)	–3.65	< .001*
ConN–Vowel	.05 (.07)	–.02 (.09)	.11 (.11)	–.05 (.09)	–.09 (.03)	–2.68	.010
ConN–Read	–.02 (.05)	–.08 (.07)	.06 (.07)	–.13 (.06)	–.128 (.03)	–4.47	< .001*
ConF–Vowel	.06 (.09)	–.05 (.08)	.08 (.12)	–.01 (.08)	.02 (.03)	.437	.664
ConF–Read	–.02 (.06)	–.11 (.08)	.03 (.09)	–.09 (.07)	–.02 (.03)	–.709	.482
Vowel–Read	–.07 (.07)	–.07 (.06)	–.05 (.07)	–.08 (.06)	–.04 (.02)	–1.58	.120

Note. Mean and standard deviation/standard error values for the slope difference scores are shown for the task differences, Group × Task differences, and Group × Task × Noise differences. Significance was based on a Bonferroni correction for six comparisons ($p < .05/6 = .008$). PD = Parkinson's disease; HC = healthy control; ConvoN = conversation (near); ConvoF = conversation (far).

*Significant at $p < .008$ (.05/6 comparisons).

and greater communicative demands. It is possible that, in PD, either this increased priority is not engaged for cognitive reasons, or feedback monitoring processes for motor execution are either not appropriately initiated or excessively inhibited. Previous work suggests possible frontostriatal impairment in IWPD based on dual-task studies (Ho et al., 2002; Whitfield et al., 2019). Future studies are recommended that systematically manipulate attentional demands (e.g., cognitively demanding dual tasks) and speech tasks with varying communicative intent to further elucidate the current findings and explanations.

The current study expands on previous work by Ho et al. (1999), who found that IWPD failed to adjust their intensity (during positive-direction AIF-level testing only) in a conversation task, and results from studies of altered feedback in reading and counting tasks, which found that participants with PD respond similarly to controls (Coutinho et al., 2009; Ho et al., 1999). Although the current study found reduced compensations by the PD group in the conversation tasks, adjusting the interlocutor distance did not appear to impact this group difference. Thus, the PD group did not display an overt deficit in distance judgment as it pertained to conversing with a listener. Rather, the PD group displayed an overall disruption in the regulation of speech intensity and abnormal use of altered auditory feedback in both conversation tasks.

Background Noise

Consistent with previous studies (Adams, Dykstra, et al., 2006; Garnier et al., 2010; Ho et al., 1999; Lane & Tranel, 1971; Pick et al., 1989), the presentation of background noise was found to elicit an increase in speech intensity (i.e., Lombard response) in both experimental groups (participants with PD and control participants). IWPD-related hypophonia have been shown in previous studies to display an "overall gain reduction" for speech intensity and a gradually decreasing signal-to-noise ratio with increasing background noise (Adams, Dykstra, et al., 2006; Ho et al., 1999). The abnormal response to AIF in the PD group appeared to be differently affected by the background noise, such that although the PD group produced a flatter slope in the AIF response than the controls in no noise, in the context of 65 dB SPL background noise, the group difference was emphasized (the PD group was observed to produce a much flatter slope of the AIF function compared to the control group). It appears that when IWPD are speaking in a noisy environment, abnormal sensorimotor integration for speech intensity regulation is more pronounced. Put differently, when the environmental condition requires a change in speech intensity, the range of available speech intensity or the intensity capacity is not appropriately engaged.

Although auditory-related dysfunction has been observed in PD and may be caused by loss of dopaminergic neurons in the basal ganglia and subsequent projections to the inferior colliculus, medial geniculate nucleus, and temporal cortex (Lukhanina et al., 2009), the Lombard effect has been demonstrated in a wide range of nonhuman animals, and evidence suggests that the primary neural mechanisms for this response are subcortical (for a review, see Luo et al., 2018). However, other studies have demonstrated that humans have a certain degree of control over the response, and therefore, a volitional neural network is also proposed (Luo et al., 2018; R. Patel & Schell, 2008). Additionally, results from the current study suggest that the background noise effect was even more pronounced during the conversation at a near distance speech task. Thus, it is possible that the group differences in background noise may be related to the reduced ability of the PD group to appropriately engage mechanisms in tasks with clear communicative goals. In the control group, the background noise may be eliciting a feedback monitoring process that is distinct from that used in the no-noise condition due to the fact that speech intelligibility is at risk of being compromised in noise—a communicative goal hypothesis, as it relates to the Lombard response. Previous studies have considered this as a possible explanation for the Lombard effect, such that this reflex is engaged so as to mediate reduced speech intelligibility and maintain clarity of speech when communicating (R. Patel & Schell, 2008).

Summary of Discussion

The current study contributes to our understanding of hypophonia in PD and advances our specific understanding of the role of auditory perception in PD-related hypophonia. IWPD were observed to produce a reduced or flatter AIF response compared to the neurologically healthy control participants in this study. Results suggest that IWPD are unable to appropriately integrate the auditory information of their speech for the production of intended intensity levels (feedforward processes). These findings were especially apparent in contexts with naturalistic communication demands and speaking conditions. The current study results suggest the importance of communication and social considerations in theoretical models of speech motor control.

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Appendix

Zero-Intercept Analysis of Variance Results and Descriptive Statistics

Table A1. Zero-intercept three-way Group × Speech Task × Background Noise condition analysis of variance results.

Variable	*df*	*F*	*p*	η_p^2
Between subjects				
Group	1, 46	.192	.663	.004
Within subjects				
Task	2.32, 106.5	69.41	**< .001***	.601
Task × Group	2.32, 106.5	1.30	.278	.027
Background Noise	1, 46	24.77	**< .001***	.350
Background Noise × Group	1, 46	1.03	.316	.022
Task × Background Noise	2.07, 95.3	36.32	**< .001***	.441
Task × Background Noise × Group	2.07, 95.3	3.23	.079	.066

*Significant at $p < .05$.

Table A2. Zero-intercept marginal means and standard deviations related to the speech tasks for the Parkinson's disease (PD; *n*= 25) and healthy control (HC; *n* = 23) groups.

	PD		HC	
Speech task	***M***	***SD***	***M***	***SD***
Conversation near	67.89	3.04	68.48	3.04
Conversation far	70.29	3.24	71.43	3.24
Vowel	69.88	2.88	69.84	2.87
Reading	65.50	3.47	65.15	3.46

Table A3. Zero-intercept marginal means and standard deviations related to the noise conditions for the Parkinson's disease (PD; *n* = 25) and healthy control (HC; *n* = 23) groups.

	PD		HC	
Noise condition	***M***	***SD***	***M***	***SD***
No noise	67.65	3.12	67.60	3.13
65-dB noise	69.14	2.74	69.85	2.74

Table A4. Zero-intercept descriptive statistics related to the noise and speech task interaction for all participants.

Noise condition	Task	*M*	*SD*
No noise	Conversation near	66.16	3.67
	Conversation far	69.15	3.92
	Vowel	69.12	3.30
	Reading	65.93	4.26
65-dB noise	Conversation near	70.25	3.30
	Conversation far	72.51	3.24
	Vowel	70.57	3.33
	Reading	64.66	3.60